Theoretical Derivation of Value of Travel time and Demand Elasticity: Evidence from NJ Turnpike Toll Road

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ABSTRACT

This paper explores NJ Turnpike (NJTPK) users’ valuation of travel time (VOTT) and their responsiveness to toll changes (elasticity) for different trip purposes in the presence of time-of-day pricing. An econometric model is developed by extending DeSerpa’s classical time allocation model and relaxing constant marginal utility assumption. This model joins users’ time-of-day choices in the presence of time-of-day pricing and departure/arrival-time restrictions. Using traveler survey data collected to evaluate NJTPK time-of-day pricing program, VOTT and elasticity functions for different travel periods and trip purposes are estimated. The main contribution of the empirical results is that in the presence of time-of-day pricing applications, when the main choice of commuters is travel-period rather than alternative routes/modes, VOTT and elasticity of a user are influenced by the travel-period, trip purpose, departure time, desired arrival time, and early/late arrival amount in addition to the travel time, toll amount and income parameters. Mean VOTT values range between $15/hr and $20/hr, while mean elasticities range between -0.06 and -0.18 depending on the choice of travel period and trip purpose. Elasticities calculated from traffic and travel time data reveal estimates in the range of -0.15 and -0.31. These relatively high VOTT and low elasticities, explaining the low responses to the minor toll differentials introduced by the time-of-day pricing program, can have major implications in determining toll differentials for future time-of-day pricing implementations in highly urbanized areas where income levels are relatively high, user flexibility is low and possibilities to shift other modes/routes are limited.
INTRODUCTION

For many years traffic management strategies, such as time-of-day pricing programs, have been proposed to reduce peak-period congestion by providing higher toll levels under congested conditions and lower tolls at less congested times. In the existence of time-of-day pricing, commuters traveling between an origin-destination (O-D) pair can either pay higher tolls to save on travel time; they can shift to off-peak periods, or use alternative routes/modes to avoid tolls but experience higher travel times. Another possibility is that with the correct toll peak times would not be highly congested, thus travelers with high value of time and who want to travel at peak periods can shift to peak hours.

The relationship between toll, travel time and consequently the efficiency of time-of-day pricing raises two fundamental questions of how much commuters are willing to pay to save travel time, i.e. commuters’ value of travel time (VOTT) (\(1\)), and their responsiveness to price changes, i.e. demand elasticity with respect to toll (\(2\)).

In practice, these two parameters are difficult to assess; since there are many variables affecting VOTT and elasticity as a result of time-of-day pricing, but there are very few time-of-day pricing applications and very limited research has been done to estimate these parameters (3,4). To this extent, NJ Turnpike (NJTPK) recently implementing time-of-day pricing can help to investigate commuters’ VOTT and demand elasticity in the presence of time-of-day pricing.

As it will be mentioned in the “Background and Literature Review” Section, previous studies imply that commuters’ time-of-day choices along with the route/mode choices as a result of time-of-day pricing have not been thoroughly examined, yet. Likewise, developing VOTT and elasticity models using an econometric approach, and considering the departure/arrival-time restrictions, still remain to be challenged. The main contributions of the proposed methodology can be summarized as follows.

1. DeSerpa’s classical time allocation model (5) is extended by introducing additional variables and constraints (such as departure time, desired arrival time and deviation from desired arrival time) related to departure/arrival time restrictions.

2. Following the idea of relaxing constant marginal utility assumption proposed by (6), user heterogeneity is introduced, and user specific VOTT and demand elasticity functions are derived for each travel-period and trip-purpose.

3. The proposed models are estimated using NJTPK traveler survey data (7) and significance level of the additional parameters are tested.

4. Aggregate elasticity values are calculated from NJTPK traffic data, and compared with the user specific elasticity values derived from econometric utility models.

The paper is organized as follows. First, brief outline of the NJTPK is provided followed by the detailed background and literature review of VOTT and elasticity concepts. After describing the data sets, derivation and empirical results of the econometric utility, VOTT and elasticity functions estimated from the traveler survey data are presented. Then, elasticity functions derived from the proposed methodology are compared with the elasticities calculated from disaggregate traffic data. In the last section conclusions and discussions are presented.

NJTPK TIME-OF-DAY PRICING PROGRAM

NJTPK is a 148 mile-toll road with total traffic exceeding 700,000 veh/day. The toll-road extends from Delaware Memorial Bridge in the South New Jersey (NJ) to George Washington Bridge in New York City (NYC). Toll levels increase as the distance traveled increases and number of axles of the vehicle increases. Since September, 2000, time-of-day pricing has been

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applied at NJTPK to encourage peak-period commuters to shift to off-peaks to reduce the congestion during peak-hours. Only passenger cars with E-ZPass tag are eligible for time-of-day pricing, and cash users’ tolls are higher than E-ZPass users irrespective of time-of-day. During peak hours and shoulders, more than 90% of the vehicles are passenger cars with E-ZPass (8). Peak hour tolls are effective on weekdays from 7:00 to 9:00AM and from 4:30 to 6:30PM. In January, 2003, toll levels for each period and vehicle type were increased. Currently, for passenger cars with E-ZPass tag peak tolls are 15% higher than the off-peak tolls (10-60 cents).

NJTPK has some facility specific properties distinguishing it from other toll facilities in the U.S. First, most of the other major toll facilities (SR91, San Diego Route-15, Houston I-10, and Houston US-290) provide alternative modes/routes with lower prices but higher travel times. However, for the NJTPK case, similar to Lee County Bridges toll facility, traffic impact study indicate that the toll increase in January 2003, did not have a statistically significant impact on the traffic flows observed at NJTPK. More importantly, the disaggregate analysis conducted to determine the reasons of traffic shift indicate that given the small toll differential between peak and off-peak periods commuters respond more to congestion (lower travel times) than slightly higher tolls (9). In addition, descriptive analysis of traveler surveys indicate statistically insignificant shift to other modes/routes from NJTPK after the introduction of time-of-day pricing (7), stating that NJTPK users choose only between peak and off-peak periods depending on their valuation of travel time and response to toll changes. This is in fact expected, since NJTPK is almost the only alternative for a large number of trips to various important employment centers in and outside the State including NYC. NJ has an excellent train system; however it does not provide an alternative to most NJTPK users residing far from train stations. In addition, the only parallel route to NJTPK is Route-1/9, which is an arterial road, and is not an attractive alternative due to extensive amount of traffic signals. Second, given that only passenger cars with E-ZPass are eligible to time-of-day pricing, E-ZPass users take advantage of both lower tolls and shorter delays at toll booths, which reduce their total costs compared to cash users, and make time-of-day pricing more feasible and attractive for them.

BACKGROUND AND LITERATURE REVIEW

Value of Travel time

VOTT can be defined as the marginal rate of substitution of travel time for money in commuters’ utility function, which represents the relative desirability of the available alternatives (1). Small, back in 1992, (10) generalized from a review of many estimates that average VOTT for journeys to work is about 50% of the gross wage rate but there were variations from 20% to 100% among different cities, and larger variations among population subgroups. However, in (1), it is argued that this claim is invalidated by more recent studies. Most of these previous studies estimate VOTT of commuters based on utility functions estimated from discrete choice models using traveler survey data (1,11,12,13,14,15). The variables to be included into the utility model are selected using a trial-and-error approach, i.e. variables improving the goodness-of-fit of the model the most are included (14). Then, VOTT is calculated as the ratio between the coefficient of travel time and coefficient of the travel cost in the utility function. TABLE 1 shows summary of these studies. The main drawback of these studies is that they do not have an econometric approach like time allocation models. In addition, the proposed models are mostly specific to route/mode choices rather than time-of-day choices.
TABLE 1 VOTT estimation results based on discrete choice models

<table>
<thead>
<tr>
<th>Study</th>
<th>Area</th>
<th>Model</th>
<th>VOTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownstone et al. (11)</td>
<td>I-15, San Diego</td>
<td>RP, Conditional Logit</td>
<td>$22/hr (morning)</td>
</tr>
<tr>
<td>Hensher (12)</td>
<td>Australia</td>
<td>SP, heteroscedastic Logit</td>
<td>$6.34/hr-$10.2/hr</td>
</tr>
<tr>
<td>Calfee et al. (13)</td>
<td>Michigan</td>
<td>SP, Multinomial Logit</td>
<td>$4/hr</td>
</tr>
<tr>
<td>Sullivan (14)</td>
<td>SR 91, California</td>
<td>RP, Multinomial Logit</td>
<td>$8-$16/hr</td>
</tr>
<tr>
<td>Hultkrantz et al. (15)</td>
<td>Sweden</td>
<td>SP, Probit</td>
<td>$6.43/hr</td>
</tr>
</tbody>
</table>

Numerous theoretical and empirical studies about commuters’ time-of-day choices have been conducted for about 25 years (see, for example, 14,16,17,18,19). De Palma (19) emphasizes that commuters change their departure times as well as their modes/routes when time-of-day dependent policies are implemented. Yet, either these studies are not explored in the context of time-of-day pricing, or they do not investigate VOTT of commuters as a result of time-of-day pricing. In (14) time-of-day choices of SR91 commuters is investigated in the existence of variable tolls, however based on the estimation results it is stated that given the complexity of these models, time-of-day and mode choices could not be modeled simultaneously. Additionally, in (11) it is stated that it is possible for commuters to change their departure times in response to changes in toll and congestion levels, however due to insufficient data to jointly model departure time and mode choice, only VOTT as a result of mode choice is considered.

With the development of time allocation models, econometric background for utility models is introduced (5,20,21,22,23). In most of these models, discrete choice utility model is either assumed to be linearly dependent on travel time and travel cost (23), or linearly approximated using the Cobb-Douglass form of utility (22). Blayac et al. (6) propose a particular derivation process for the utility function to develop a functional form for VOTT by relaxing constant marginal utility assumption, and emphasize that this functional form ought to be tested empirically. Nonlinearity of price and travel time is introduced into the model estimation using Box-Cox transforms (24). Even though these models provide an econometric background for the utility models and VOTT functions, either they are not applied in the time-of-day pricing environment, or they do not consider choice of travel period as an alternative.

**Demand Elasticity**

Elasticity of demand is an empirical measure that determines the responsiveness of users to price changes (2), and defined as the percentage change in demand in response to 1% change in price. In (25), San Francisco, California area bridge elasticities are estimated using traffic counts, and the elasticities are found to be -0.1 on average. The study performed by (26) indicates an average elasticity value of -0.1 for the NYC bridges and tunnels. The elasticities for each crossing of the Triborough Bridge and Tunnel Authority in NYC estimated from traffic data range between -0.085 and -0.386 (27). In addition, elasticities estimated for the Lee County Florida Variable Pricing Project, using traffic counts are found between -0.03 and -0.36 depending on the time-of-day (28). In these studies, except Lee County Project, user heterogeneity, trip purpose, or alternative routes/modes/travel periods are not considered, which would help the policy makers to understand how user specific properties affect commuters’ responses to toll changes.

With the use of discrete choice models, travel and socio-economic characteristics can be included into elasticity estimation via utility models. Based on this utility model probability of selecting a route/mode/period can be estimated and demand-elasticity can be calculated using probability values. In a study performed to estimate the elasticity values for SR91 toll road based on traveler surveys, the elasticities are found between -0.7 and -1.0 depending on time-of-day
In nested logit models are derived based on Roy’s Identity and estimate elasticity using
the Austin, Texas traveler survey data. Estimated demand elasticities are found to be between
0.022 and -0.22. Even though these studies include user heterogeneity in the elasticity estimation
via utility functions, similar to VOTT estimation, either these utility functions do not follow an
econometric approach like time allocation models, or the proposed utility models do not consider
time period choices.

DATA DESCRIPTION

Traveler Survey Data

The NJTPK traveler survey data are employed to estimate VOTT and elasticity functions
and to test the significance level of additional variables proposed in this study. The survey was
conducted by researchers at Eagleton Institute of Rutgers University (7), from computer aided
telephone interviews. Target population was defined as all individuals who have regularly used
NJTPK (at least once per week) since September 2000. The data set contains 513 complete
observations, 483 (94.2%) of which are current regular users residing in NJ. The survey
participants were asked in detail about their most recent trips in morning and afternoon peaks.
The questions include origin, destination, travel time, toll, purpose, departure-time,
desired/actual arrival time, and deviation from desired arrival time (early/late arrival amount) of
each trip, as well as the questions on socio-economic characteristics such as; income, education,
employment, age and gender.

Econometric utility models are derived for current regular NJTPK users traveling on
weekdays. After eliminating data points with missing information, data set includes 292 valid
trips; 166 (57%) of which are work, and 126 (43%) of which are leisure trips. Since work and
leisure trips have their own properties and users give different values to different trips due to
variations in goods consumption (22), models are estimated separately for each trip purpose.

Traffic Data

Disaggregate traffic data used in the elasticity estimation include vehicle-by-vehicle
entry/exit times and locations of each E-ZPass vehicle, and toll paid between October-2002 and
March-2003. To obtain the appropriate dataset for the elasticity estimation, a source code is
written in Matlab, and for each O-D pair hourly traffic and travel-time corresponding to that
specific traffic are determined. Since this data set involves traffic values that are too small to be
statistically significant and are not needed to be included in the estimation, database is further
clustered to develop clusters of vehicles that are large enough to be statistically significant.
Specifically, O-D pairs which have at least 100 veh/hr or form at least 10% of total daily traffic
are selected. Details of the clustering methodology can be found in (8). The data set obtained
from these two criteria, represents almost 80% of total flow observed on peak and peak-
shoulders.

ECONOMETRIC UTILITY MODELS

Derivation of Utility Models

The utility function formulation and constraint selection are the main issues while
constructing time allocation models. Since the purpose of this study is to investigate the
commuters’ not only route/mode choices but travel period choices in the presence of time-of-day
pricing and departure/arrival-time restrictions, it is required to extend classical time allocation
model with additional variables and constraints; such as departure time, desired arrival time and
deviation from desired arrival time (early/late arrival amount) as shown in Equations (1e)-(1h).
The mathematical formulation of the extended time allocation model is as follows.
\[
\begin{align*}
\text{Max} & \quad V(t, t_i, p_i, p, T, R, \Delta_i^\text{early}, \Delta_i^\text{late}) \\
\text{st} & \quad px + \sum_{i=0}^{N} d_i p_i = R \\
& \quad t + \sum_{i=0}^{N} d_i t_i = T \\
& \quad t_i \geq t \quad \{ \theta \} \\
& \quad e_i (t_i - t) = \Delta_i^\text{early} \quad \{ \phi \} \\
& \quad l_i (t_i + t) = \Delta_i^\text{late} \quad \{ \phi \} \\
& \quad e_i \Delta_i^\text{early} \leq \Delta_i^\text{early} \quad \{ \phi \} \\
& \quad l_i \Delta_i^\text{late} \leq \Delta_i^\text{late} \quad \{ \psi \} \\
& \quad d_i, e_i, l_i = (0,1) \quad \{ q, t_i, p_i, p, T, R, \Delta_i^\text{early}, \Delta_i^\text{late} \} \geq 0
\end{align*}
\]

where;

\(i = \text{Travel choice index}\)

\(V = \text{Utility}\)

\(R = \text{Income level (in thousands of dollars)}\)

\(t = \text{Time spent in activities other than travel (in hours)}\)

\(t_i = \text{Minimum time requirement to travel on travel choice } i \text{ (in hours)}\)

\(t_{oi} = \text{(desired arrival time) - (departure time to travel on travel choice } i) \text{ (in hours)}\)

\(T = \text{Total available time (in hours)}\)

\(p_i = \text{Cost of travel on travel choice } i \text{ (in dollars)}\)

\(p = \text{Cost of goods other than travel (in dollars)}\)

\(x = \text{Consumption of goods other than travel}\)

\(\Delta_i^\text{early} = \text{Maximum flexibility for early arrival (in hours)}\)

\(\Delta_i^\text{late} = \text{Maximum flexibility for late arrival (in hours)}\)

\(\Delta_i^\text{early} = \text{Early arrival amount for travel choice } i \text{ (in hours)}\)

\(\Delta_i^\text{late} = \text{Late arrival amount for travel choice } i \text{ (in hours)}\)

\(d_i = \begin{cases} 1, & \text{if travel choice } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases}\)

\(e_i = \begin{cases} 1, & \text{if early arrival is observed when travel choice } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases}\)

\(l_i = \begin{cases} 1, & \text{if late arrival is observed when travel choice } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases}\)

The objective function of the optimization problem (Equation 1a), represents an unknown user specific utility as a function of time spent to travel and perform other activities, cost of travel and other activities, income, available time, departure time, desired arrival time and early/late arrival amount. Constraint 1b states that total income is allocated between travel costs and cost of goods other than travel. Constraint 1c ensures individuals allocate their total time between work/leisure and trip related activities. Constraint 1d states that each period has its minimal time requirement. Constraints 1e-1f state users can either arrive early or late to their
destination; while constraints 1g-1h ensure they arrive within the maximum arrival flexibility. Finally, parameters in the parentheses refer to the Lagrangian multiplier of each constraint. From this proposed time allocation model, Ozbay et al. (7) showed how to derive the expression for the derivative of the representative utility function for the early arrival case based on Lagrangian of the optimization problem and envelope theorem (30). The mathematical form of the differential utility function is shown in the equation below.

\[
dV_i = -\lambda(dp_i - dR_i) + \phi dT - k_i dt_i - \theta_i (dt_i - d\Delta_{early})
\] (2)

In this formulation, \(\lambda\) and \(\phi\) represent the marginal utility of having additional income and available time, respectively; \(k_i\) is the marginal utility of decreasing time requirements, and \(\theta_i\) is the marginal utility of reducing the deviation from desired arrival time. Based on the total differential of the utility function Ozbay et al. (7) obtained the analytical form of the utility function by relaxing constant marginal utility assumption, and approximating the utility function by first order Taylor expansion around the average point of marginal utilities (6). The final mathematical form of the utility function for travel choice \(i\) is shown below (For the detailed derivation of the utility functions please refer to (7)).

\[
V_i = a_i R + a_i R_{dep} - a_i t_i p_i - a_i t_i a_{early} - a_i \Delta_{early} - a_i \Delta_{early} + a_{13} R_{dep} + a_{15} R_{early} + a_{16} R_{early} - a_{16} \Delta_{early} - t_{dep}
\] (3)

Equation 3 shows that the utility of choice \(i\) increases with increasing income and decreasing travel time, travel cost, departure time, desired arrival time, and deviation from desired arrival time. When this equation is compared with other models developed in the literature, it is clear that departure time related parameters affect the utility function and the travel choice behavior as a result of time-of-day pricing. This proposed utility model does not treat choices of route, mode or travel period separately; instead it handles all travel choices simultaneously considering the departure/arrival time restrictions of commuters.

**Estimation of Utility Models**

Since NJTPK users choose among different travel periods rather than alternative route/modes, model estimation can only be conducted based on users’ choices of travel period. For each trip purpose, variables can be categorized into two parts; trip related variables and traveler related variables. TABLE 2 shows the definition of the variables.

**TABLE 2 Definition of the independent variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trip Related</strong></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Travel time, given time-of-day, destination</td>
</tr>
<tr>
<td>Toll</td>
<td>Toll paid per occupancy, in dollars</td>
</tr>
<tr>
<td>Early</td>
<td>Amount of early arrival time</td>
</tr>
<tr>
<td>Late</td>
<td>Amount of late arrival time</td>
</tr>
<tr>
<td>dep. Time</td>
<td>(Departure time) – (Desired arrival time)</td>
</tr>
<tr>
<td>distance</td>
<td>distance traveled at the NJTPK</td>
</tr>
<tr>
<td><strong>Traveler Related</strong></td>
<td></td>
</tr>
<tr>
<td>Income</td>
<td>Income level</td>
</tr>
<tr>
<td>Age</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>1 if female, 0 otherwise</td>
</tr>
<tr>
<td>Education</td>
<td>1, if the user has at least bachelor degree, 0 otherwise</td>
</tr>
<tr>
<td>Employment</td>
<td>1, if the user is manager or professional, 0 otherwise</td>
</tr>
<tr>
<td>E-ZPass</td>
<td>1 if the user owns E-ZPass tag, 0 otherwise</td>
</tr>
</tbody>
</table>
Since time-of-day pricing at NJTPK is only applicable to E-ZPass users, qualification for a toll discount at off-peak periods is fully determined by E-ZPass ownership. To observe the relative effects of getting an E-ZPass tag on the period choice, a nested logit model is estimated for both work and leisure trips. In this type of model, in the upper nest, model regarding transponder-ownership choice is derived. Then in the lower nest, conditional on the transponder-ownership choice, utility model for choice of travel period is estimated.

Depending on the trip purpose, probability of selecting a specific travel period is calculated as the joint probability of transponder-ownership choice and the conditional travel period choice. The mathematical formulation of nested logit model is as follows (31).

\[
P_{ni} = P_{nC_k} P_{nc_i} \quad P_{ni} = \frac{\exp(\beta X_{ni} / \rho_k)}{\sum_{j \in C_k} \exp(\beta X_{nj} / \rho_k)} \cdot \frac{\exp(\rho_k I_{nk} + \alpha Y_{nk})}{\sum_{l=1}^{m} \exp(\rho_l I_{nl} + \alpha Y_{nl})}
\]

where;

- \( I_{nk} = \ln \left( \sum_{j \in C_k} \exp(X_{nj} / \rho_k) \right) \)
- \( i = \text{Index for choice of travel period (1 = pre-peak, 2 = peak, 3 = post-peak)} \)
- \( k = \text{Index for transponder-ownership choice (1 = E-ZPass, 2 = Cash)} \)
- \( n = \text{Index for individual user (n = 1,..,N) (N = 166 for work trips) (N = 126 for leisure trips)} \)
- \( C_k = \text{Set of transponder-ownership choice (E-ZPass and cash)} \)
- \( B_j = \text{Set of choice of travel period (pre-peak, peak, post-peak)} \)
- \( P_{ni} = \text{Probability of selecting travel period } i \text{ for individual } n \)
- \( P_{nC_k} = \text{Marginal probability of choosing a transponder alternative in set } C_k \)
- \( P_{ni/C_k} = \text{Conditional probability of choosing period } i \text{ given that a transponder alternative } k \text{ is chosen} \)
- \( \beta = \text{Coefficients of the utility function for period choice} \)
- \( X_{ik} = \text{Vector of variables included in the period choice model} \)
- \( m = \text{Number of transponder-ownership choice} (m = 2) \)
- \( \rho_k = \text{Inclusive parameter for the transponder-ownership choice} \)
- \( \alpha = \text{Coefficients of the utility function for transponder-ownership choice} \)
- \( Y_{nk} = \text{Vector of variables included in the transponder-ownership choice model} \)

The quantity \( I_{nk} \) links the upper and lower models by bringing information from the lower nest into the upper nest (31). The variables to be included in each nest are determined based on their relative effects. Since traveler related variables affect the transponder-ownership choice; these variables are included in the upper nest. Likewise, since trip related variables and income level affect the choice of travel period conditional on the transponder-ownership choice, these variables are included in the lower nest.

Cash users pay the same toll for all periods, thus to investigate effects of toll on the cash users’ period choice, cash users’ model is first estimated by including and then excluding toll related variables. For cash users toll related variables are found to be irrelevant in period choice and reduce the model fitness, as expected. Therefore, in the final estimation toll related variables...
are excluded from the cash users’ utility models. Using the nested logit model described above, four different econometric models are estimated depending on the trip purpose and transponder-ownership choice. The utility functions of each nest for E-ZPass and cash users are shown in TABLE 3. The variables provided in each function are statistically significant at 90% confidence level.

**TABLE 3  Econometric utility functions for E-ZPass users**

<table>
<thead>
<tr>
<th>Trip type</th>
<th>Period</th>
<th>Utility Function (E-ZPass users)</th>
<th>Utility Function (Cash Users)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work (1)</td>
<td>Pre (1)*</td>
<td>$0.58 \text{employment}_i + 0.05 \text{age}_i - 0.86 \text{education}_i + 0.55 \text{female}_i$</td>
<td>$0.064 R_i - 0.15 t_{11} \overline{R}<em>i + 0.106 t</em>{12} \overline{P}<em>{11} - 0.25 p</em>{12} - 0.22 t_{11}$</td>
</tr>
<tr>
<td>Peak (2)**</td>
<td></td>
<td>$0.54 \text{employment}_i + 0.04 \text{age}_i - 1.02 \text{education}_i + 0.55 \text{female}_i$</td>
<td>$0.05 R_i - 0.14 R_{12} - 0.2 t_{12} P_{22} - 0.24 p_{22} - 0.48 t_{12} - 0.18 t_{21}$</td>
</tr>
<tr>
<td>Post (3)**</td>
<td></td>
<td>$0.31 \text{employment}_i + 0.05 \text{age}_i - 0.969 \text{education}_i + 0.58 \text{female}_i$</td>
<td>$0.07 R_i - 0.139 R_{12} - 0.26 t_{12} P_{12} - 0.39 p_{12} - 0.34 t_{12} - 0.24 t_{13}$</td>
</tr>
<tr>
<td>Leisure (2)</td>
<td>Pre (1)*</td>
<td>$0.05 \text{age}_i + 0.88 \text{education}_i + 0.39 \text{female}_i$</td>
<td>$0.082 R_i - 0.18 R_{12} \frac{t_{11}}{11} - 0.1 t_{11} P_{11} - 0.31 p_{11} - 0.44 t_{11}$</td>
</tr>
<tr>
<td>Peak (2)**</td>
<td></td>
<td>$0.05 \text{age}_i + 0.99 \text{education}_i + 0.36 \text{female}_i$</td>
<td>$0.082 R_i - 0.18 R_{12} \frac{t_{11}}{11} - 0.1 t_{11} P_{11} - 0.31 p_{11} - 0.44 t_{11}$</td>
</tr>
<tr>
<td>Post (3)**</td>
<td></td>
<td>$0.06 \text{age}_i + 1.14 \text{education}_i + 0.46 \text{female}_i$</td>
<td>$0.08 R_i - 0.15 R_{12} \frac{t_{11}}{11} - 0.18 t_{11} P_{11} - 0.23 p_{11} - 0.53 t_{13}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trip type</th>
<th>period</th>
<th>Utility Function (Cash Users)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work (1)</td>
<td>Pre (1)*</td>
<td>$-0.34 \text{employment}_2 - 0.05 \text{age}_2 + 1.54 \text{education}_2 - 0.52 \text{female}_2$</td>
</tr>
<tr>
<td>Peak (2)**</td>
<td></td>
<td>$-0.42 \text{employment}_2 - 0.05 \text{age}_2 + 0.91 \text{education}_2 - 0.52 \text{female}_2$</td>
</tr>
<tr>
<td>Post (3)**</td>
<td></td>
<td>$-0.72 \text{employment}_2 - 0.05 \text{age}_2 + 1.33 \text{education}_2 - 0.57 \text{female}_2$</td>
</tr>
<tr>
<td>Leisure (2)</td>
<td>Pre (1)*</td>
<td>$-0.05 \text{age}_2 - 1.2 \text{education}_2 - 0.23 \text{female}_2$</td>
</tr>
<tr>
<td>Peak (2)**</td>
<td></td>
<td>$-0.05 \text{age}_2 - 1.15 \text{education}_2 - 0.23 \text{female}_2$</td>
</tr>
<tr>
<td>Post (3)**</td>
<td></td>
<td>$-0.05 \text{age}_2 - 1.03 \text{education}_2 - 0.29 \text{female}_2$</td>
</tr>
</tbody>
</table>

*pre: 6-7A.M. and 3:30-4:30P.M. **peak: 7-9A.M. and 4:30-6:30P.M. ***post: 9-10A.M. and 6:30-7:30P.M
VOTT FUNCTIONS

Derivation of VOTT Functions

The user specific VOTT functions can be calculated based on the ratio between partial derivative of the utility function (Equation-3) with respect to travel time and the partial derivative of the utility function with respect to travel cost. Equation-5 depicts the VOTT function derived from the proposed methodology. This function shows that apart from travel time, travel cost and income; departure time, desired arrival time and early/late arrival amount influence the commuters’ VOTT. When this equation is compared with the model developed by (6), it can be concluded that the signs of variables that are common to both models are the same. However, it is clear that departure and arrival times have an effect on the VOTT of a commuter as a result of time-of-day pricing.

\[
\frac{\partial V_t}{\partial t_i} = \frac{a_2 R - a_4 p_i - a_5 - a_{16} - 2a_{12} - a_{15} \Delta_{\text{early}}}{a_{16} R - a_4 t_i - a_5 - 2a_{11} p_i - a_{14} \Delta_{\text{early}} - a_{16} t_i}
\]

Estimation of VOTT Functions

Using the VOTT formulation given in Equation-5, for each trip purpose and period choice, user specific VOTT functions are estimated. Since toll related parameters are found to be statistically insignificant for cash users, VOTT functions are calculated only for E-ZPass users. TABLE 4 presents the VOTT functions, mean and standard deviation of VOTT values for each estimated model.

The econometric model derived and estimated in this study claim that VOTT for a user is highly influenced by the trip purpose, choice of travel-period, income, toll, travel time, departure time and desired arrival time. Mean VOTT values range between $15/hr and $20/hr depending on travel-period and trip purpose. VOTT values of work trips are higher compared to leisure trips, and peak period users have the highest VOTT values indicating that commuters making work trips and peak period commuters are willing to pay higher amount of money to save travel time.

TABLE 4 VOTT Functions of E-ZPass Users

<table>
<thead>
<tr>
<th>Trip Purpose</th>
<th>Period</th>
<th>VOTT Function</th>
<th>Mean VOTT</th>
<th>St. Dev. VOTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work (1)</td>
<td>pre (1)</td>
<td>$\frac{\partial V_{11}}{\partial t_{11}} = -0.106 p_{11} - 0.9 t_{11} - 0.15 R - 0.22$</td>
<td>$16.72/hr$</td>
<td>$2.77/hr$</td>
</tr>
<tr>
<td></td>
<td>peak (2)</td>
<td>$\frac{\partial V_{12}}{\partial t_{12}} = -0.2 p_{12} - 0.8 t_{12} - 0.3 t_{13} - 0.14 R - 0.48$</td>
<td>$19.72/hr$</td>
<td>$2.89/hr$</td>
</tr>
<tr>
<td></td>
<td>post (3)</td>
<td>$\frac{\partial V_{13}}{\partial t_{13}} = -0.26 p_{13} - 0.62 t_{12} - 0.13 t_{13} - 0.139 R - 0.34$</td>
<td>$17.35/hr$</td>
<td>$2.16/hr$</td>
</tr>
<tr>
<td>Leisure (2)</td>
<td>pre (1)</td>
<td>$\frac{\partial V_{21}}{\partial t_{21}} = -0.1 p_{21} - 0.5 t_{21} - 0.18 R - 0.44$</td>
<td>$17.03/hr$</td>
<td>$2.17/hr$</td>
</tr>
<tr>
<td></td>
<td>peak (2)</td>
<td>$\frac{\partial V_{22}}{\partial t_{22}} = -0.15 p_{22} - 1.09 t_{22} - 0.15 t_{23} - 0.2 R - 0.7$</td>
<td>$17.16/hr$</td>
<td>$2.03/hr$</td>
</tr>
<tr>
<td></td>
<td>post (3)</td>
<td>$\frac{\partial V_{23}}{\partial t_{23}} = -0.18 p_{23} - 0.92 t_{23} - 0.15 R - 0.43 t_{23} - 0.53$</td>
<td>$15.33/hr$</td>
<td>$2.09/hr$</td>
</tr>
</tbody>
</table>
Although relative magnitude of VOTT values for peak/peak-shoulders and work/leisure trips are similar to the results of other similar studies, mean VOTT values of NJTPK users are higher than most of the other toll facilities. The reason behind this difference can be explained with the several facts specific to the NJTPK. First, unlike other studies, no statistically significant shift to alternative routes/modes from the NJTPK is observed (7,8,9). In addition, as obtained from the descriptive analysis of the NJTPK traveler survey data (7), NJTPK commuters do not have much flexibility, and they mainly adapt their schedules to avoid congestion rather than to take advantage of cheaper tolls. More importantly, current NJTPK users have relatively high income levels ($82,000/yr) (7), compared to NJ median income in 2003 ($55,932) (32).

DEMAND ELASTICITY ESTIMATION FROM TRAVELER SURVEY DATA

Derivation of Demand Elasticity Functions

When elasticity values are estimated using discrete choice models, demand elasticity represents the responsiveness of a user’s probability of choosing a period to a change in the toll level. In the case of nested logit model, user specific elasticity function $E_{P_{ni}}$, depending on the choice of period, can be given by the following equations:

$$E_{P_{ni}} = \frac{\partial P_{ni}}{\partial P_{ni}} \cdot \frac{P_{ni}}{P_{ni}}$$

$$E_{P_{ni}} = \frac{\partial P_{ni}}{\partial P_{ni}} \frac{\exp(\beta X_{ni} / \rho_k) \cdot \exp(\rho_k I_{nk} + \alpha Y_{nk})}{\sum_{j \in C_i} \sum_{l=1}^{m} \exp(\rho_k I_{nl} + \alpha Y_{nl})} \cdot \frac{P_{ni}}{\exp(\beta X_{ni} / \rho_k) \cdot \sum_{j \in C_i} \sum_{l=1}^{m} \exp(\rho_k I_{nl} + \alpha Y_{nl})}$$

Since the variables attributed to transponder-ownership choice are independent of the toll amount; these variables are considered as constants in the partial derivative of the probability function with respect to toll. The reduced elasticity formulation for the nested logit model becomes as follows. The detailed derivation of the elasticity formulation can be found in (7).

$$E_{P_{ni}} = \left(1 - P_{ni} + \left(1 - P_{ni/C_i} \left(\frac{I}{\rho_k} - 1\right)\right) \cdot (\partial \beta X_{ni} / \partial P_{ni}) \cdot P_{ni}$$

Estimation of Demand Elasticity Functions

TABLE 5 summarizes user specific elasticity functions and mean elasticity values estimated from traveler survey data. The demand elasticity is affected from toll, travel time, inclusive parameter of the transponder-ownership choice, and joint and conditional probability of selecting a period (i.e. departure time, desired arrival time, early/late arrival amount, and other travel and socio-economic characteristics of the users).

Very low mean elasticity values indicate a very inelastic demand with respect to toll changes. Additionally, work trip elasticities are lower than leisure trip elasticities, and peak period elasticities are lower compared to peak-shoulder elasticities. This trend is consistent with the VOTT values stating that peak-period users making work trips are willing to pay higher amount of money to save travel time, therefore less sensitive to toll values.

Depending on the trip purpose, mean elasticities range between -0.06 and -0.08 for peak period, and between -0.11 and -0.18 for peak-shoulders. In terms of the impacts on traffic, these elasticities mean that 10% increase in peak tolls (increase in January 2003) would reduce percent
share of peak-period traffic between 0.6% and 0.8%. Similarly, a 5% increase in off-peak tolls (increase in January 2003) would reduce the percent share of peak-shoulder traffic between 0.55% and 0.9%. These low elasticity values are consistent with the traffic impact analysis results indicating that the toll increase in January 2003 did not have a statistical significant impact on the travel patterns of the NJTPK users (8,9).

**TABLE 5 Elasticity Functions of E-ZPass Users**

<table>
<thead>
<tr>
<th>trip type</th>
<th>period</th>
<th>Elasticity Function</th>
<th>Mean Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work (1)</td>
<td>Pre (1)</td>
<td>$E_{P_{a1}} = \left(1 - P_{a1}\right) + \left(1 - P_{a1/C1}\right) \left(\frac{1}{\rho_{11}} - 1\right) \cdot \left(-0.106_{a11} - 0.5_{p_{a11}} - 0.25\right)<em>{p</em>{a11}}$</td>
<td>-0.108</td>
</tr>
<tr>
<td>Peak (2)</td>
<td>$E_{P_{a2}} = \left(1 - P_{a2}\right) + \left(1 - P_{a2/C1}\right) \left(\frac{1}{\rho_{21}} - 1\right) \cdot \left(-0.2_{a21} - 0.32_{p_{a21}} - 0.24\right)<em>{p</em>{a21}}$</td>
<td>-0.06</td>
<td></td>
</tr>
<tr>
<td>Post (3)</td>
<td>$E_{P_{a3}} = \left(1 - P_{a3}\right) + \left(1 - P_{a3/C1}\right) \left(\frac{1}{\rho_{31}} - 1\right) \cdot \left(-0.26_{a31} - 0.3_{p_{a31}} - 0.29\right)<em>{p</em>{a31}}$</td>
<td>-0.11</td>
<td></td>
</tr>
<tr>
<td>leisure (2)</td>
<td>Pre (1)</td>
<td>$E_{P_{a1}} = \left(1 - P_{a1}\right) + \left(1 - P_{a1/C1}\right) \left(\frac{1}{\rho_{11}} - 1\right) \cdot \left(-0.1_{a11} - 0.24_{p_{a11}} - 0.31\right)<em>{p</em>{a11}}$</td>
<td>-0.18</td>
</tr>
<tr>
<td>Peak (2)</td>
<td>$E_{P_{a2}} = \left(1 - P_{a2}\right) + \left(1 - P_{a2/C1}\right) \left(\frac{1}{\rho_{21}} - 1\right) \cdot \left(-0.15_{a21} - 0.36_{p_{a21}} - 0.2\right)<em>{p</em>{a21}}$</td>
<td>-0.08</td>
<td></td>
</tr>
<tr>
<td>Post (3)</td>
<td>$E_{P_{a3}} = \left(1 - P_{a3}\right) + \left(1 - P_{a3/C1}\right) \left(\frac{1}{\rho_{31}} - 1\right) \cdot \left(-0.18_{a31} - 0.38_{p_{a31}} - 0.23\right)<em>{p</em>{a31}}$</td>
<td>-0.14</td>
<td></td>
</tr>
</tbody>
</table>

The relative magnitudes of peak/peak-shoulder work/leisure trip mean elasticities are similar to the results of other similar studies. Additionally, estimated elasticities are similar to the values of NYC area toll facilities; however they are lower than the toll facilities located outside NYC. These findings indicate that the small toll differential between peak and off-peak periods, the absence of alternative routes/modes specific to this area and tightness of the market situation discourage users to shift their travel periods. More specifically, current regular users do not have much flexibility to shift their current time of travel, and choose their travel periods according to their arrival time constraints or to avoid congestion rather than to take advantage of slightly cheaper tolls. This finding is supported by descriptive analysis of traveler surveys stating that among the 238 respondents who could recall the time-of-day pricing initiative, only 36 respondents (7%) changed their travel time behavior in response to time-of-day pricing, and only 22 of them increased trips along alternative routes (7).

**DEMAND ELASTICITY FROM TRAFFIC DATA**

**Derivation of Demand Elasticity**

In this section, demand elasticities are calculated using basic arc elasticity formula using percent share of traffic instead of absolute traffic values. Since NJTPK users respond more to travel time savings than toll differentials when choosing a travel period, travel cost is represented by the summation of toll and the monetary value of travel time as shown in equation-9 (8).

\[ p_i = toll_i + VOTT_i \cdot tt_i \]  

(9)

where,
Equation 10 illustrates the arc elasticity of traffic demand.

\[
E_i = \frac{1}{Q} \sum_{q=1}^{Q} \left[ \frac{D^q_{i\text{after}} - D^q_{i\text{before}}}{D^q_{i\text{before}}} \right] \frac{\left( \frac{p^q_{i\text{after}} - p^q_{i\text{before}}}{p^q_{i\text{before}}} \right)}
\]

where:

- \(i\) = Period index
- \(p_i\) = Total cost incurred to E-ZPass users traveling at period \(i\)
- \(toll_i\) = Toll paid by E-ZPass users traveling at period \(i\)
- \(VOTT_i\) = Value of travel time of E-ZPass users traveling at period \(i\)
- \(t_i\) = Travel time of E-ZPass users traveling at period \(i\)

As shown in equation-10, to estimate the elasticity at period \(i\), first for each O-D pair the change in the average percent share of traffic before and after the toll increase is calculated. Due to seasonal variation at the NJTPK traffic, demand at each month is normalized using monthly adjustment factors calculated from the NJTPK traffic data (8,9). Then, average percent share of traffic before and after the toll change is calculated as the mean of the normalized traffic demand between October-December 2002, and January-March 2003, respectively. Then, elasticity of each O-D pair is calculated by dividing the change in percent share of traffic by the change in toll level of that O-D pair. Finally, overall demand elasticity is calculated as the average of
elasticieties for all O-D pairs. TABLE 6 illustrates the overall demand elasticity at NJTPK during each period and changes in traffic corresponding to the toll increases in January 2003.

Estimation of NJTPK demand elasticities using traffic data reveal values in the range of -0.15 to -0.2 for peak-periods and in the range of -0.22 to -0.31 for peak-shoulders. One important pattern is that peak-period elasticities are lower than peak-shoulders, supporting the results obtained from traveler survey data. In addition, A.M. pre-peak elasticities are higher than A.M. post-peak elasticities, whereas P.M. post-peak elasticities are higher than P.M. pre-peak elasticities, indicating that travelers may prefer to arrive early at work and leave late. In terms of the impacts on traffic levels, these elasticities mean that 10% increase in peak tolls would reduce peak-period traffic between 1.5% and 2.0%. Similarly, a 5% increase in off-peak tolls would reduce peak-shoulder traffic between 1.1% and 1.5%.

Although these elasticities provide an overall perspective on the efficiency of NJTPK time-of-day pricing, they do not provide any information regarding commuters’ socio-economic or travel characteristics. However, methodology proposed in this paper show that socio-economic and travel characteristics (e.g. departure/arrival constraints) affect the elasticity functions in a statistically significant manner and tend to reduce the elasticity values.

### TABLE 6 Elasticity of traffic demand, traffic data

<table>
<thead>
<tr>
<th>time-period</th>
<th>mean elasticity</th>
<th>reduction in traffic as response to actual toll change in 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-7 AM</td>
<td>-0.24</td>
<td>1.18%</td>
</tr>
<tr>
<td>7-8 AM</td>
<td>-0.16</td>
<td>1.6%</td>
</tr>
<tr>
<td>8-9 AM</td>
<td>-0.15</td>
<td>1.5%</td>
</tr>
<tr>
<td>9-10 AM</td>
<td>-0.22</td>
<td>1.1%</td>
</tr>
<tr>
<td>3:30-4:30 PM</td>
<td>-0.25</td>
<td>1.25%</td>
</tr>
<tr>
<td>4:30-5:30 PM</td>
<td>-0.2</td>
<td>2%</td>
</tr>
<tr>
<td>5:30-6:30 PM</td>
<td>-0.2</td>
<td>2%</td>
</tr>
<tr>
<td>6:30-7:30 PM</td>
<td>-0.31</td>
<td>1.53%</td>
</tr>
</tbody>
</table>

### CONCLUSIONS AND DISCUSSIONS

This study has evaluated the efficiency of NJTPK time-of-day pricing via estimation of user specific VOTT and demand elasticity functions. The following improvements are implemented over past studies: (a) extension of DeSerpa's time allocation model (5) by introducing additional variables and constraints related to departure/arrival-time restrictions, (b) derivation of econometric utility, VOTT and demand elasticity functions for the travel choices using the idea of relaxing constant marginal utility assumption proposed by (6), (c) testing the significance level of the impacts of additional variables on the VOTT and elasticity of the NJTPK users using traveler survey data, and (d) comparison of econometric elasticity functions obtained from the proposed methodology with elasticity values calculated from traffic data.

The main contribution of the empirical results is that in the presence of time-of-day pricing, when the main choice of commuters is travel period rather than alternative route/modes, VOTT for a user is influenced statistically significantly by the choice of travel period, trip purpose, departure time, desired arrival time, travel time, toll amount and income. Similarly, demand elasticity of a user traveling at a specific period is affected statistically significantly from trip purpose, toll, travel time, transponder-ownership choice, and joint and conditional probability of selecting that travel period.
Mean VOTT values of E-ZPass users calculated from the derived VOTT functions range between $15/hr and $20/hr, depending on period choice and trip purpose. The highest mean VOTT value is observed for peak-period travelers making work trips, whereas the lowest mean VOTT value is observed for post-peak travelers making leisure trips. These mean VOTT values indicate that in the presence of time-of-day pricing, commuters making work trips are willing to pay higher amount of money to save on travel time, and to avoid changing time of travel to the off-peak.

Mean elasticity values of E-ZPass users calculated from user specific elasticity functions are found to be between -0.06 and -0.08 for peak-period users, and between -0.11 and -0.18 for peak-shoulder users depending on the trip purpose. Work trip elasticities are lower compared to leisure trip elasticities, and peak elasticities are lower compared to peak-shoulder elasticities. The reason behind this pattern may be due to the fact that peak-period users have less flexibility compared to peak-shoulder users due to work-related arrival constraints.

Analysis of the NJTPK time-of-day pricing program using traffic data reveals elasticities in the range of –0.15 to -0.2 for peak-periods and in the range of -0.22 to -0.31 for peak-shoulders. Similar to the results obtained from proposed methodology in this study, peak-period elasticities are lower compared to peak-shoulder elasticities. In addition, A.M pre-peak elasticities are higher than A.M post-peak elasticities, whereas P.M. post-peak elasticities are higher than P.M. pre-peak elasticities, indicating that travelers may prefer to arrive early at work and leave late.

These relatively high VOTT and low elasticity values for the NJTPK commuters can explain the low level of response to the minor toll differentials introduced by the NJTPK Authority time-of-day pricing program. In addition, these results can have major implications in determining toll differentials for future implementations of time of day pricing programs in highly urbanized areas where income levels are relatively high and user flexibility is low and possibility to shift to other modes/routes is limited.

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REFERENCES